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PAIRED STREAM–AIR TEMPERATURE MEASUREMENTS REVEAL FINE-SCALE THERMAL HETEROGENEITY WITHIN HEADWATER BROOK TROUT STREAM NETWORKS

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ABSTRACT

Previous studies of climate change impacts on stream fish distributions commonly project the potential patterns of habitat loss and fragmentation due to elevated stream temperatures at a broad spatial scale (e.g. across regions or an entire species range). However, these studies may overlook potential heterogeneity in climate change vulnerability within local stream networks. We examined fine-scale stream temperature patterns in two headwater brook trout *Salvelinus fontinalis* stream networks (7.7 and 4.4 km) in Connecticut, USA, by placing a combined total of 36 pairs of stream and air temperature loggers that were approximately 300 m apart from each other. Data were collected hourly from March to October 2010. The summer of 2010 was hot (the second hottest on record) and had well below average precipitation, but stream temperature was comparable with those of previous 2 years because streamflow was dominated by groundwater during base-flow conditions. Nonlinear regression models revealed stream temperature variation within local stream networks, particularly during warmest hours of the day (i.e. late afternoon to evening) during summer. Thermal variability was primarily observed between stream segments, versus within a stream segment (i.e. from confluence to confluence). Several cold tributaries were identified in which stream temperature was much less responsive to air temperature. Our findings suggested that regional models of stream temperature would not fully capture thermal variation at the local scale and may misrepresent thermal resilience of stream networks. Groundwater appeared to play a major role in creating the fine-scale spatial thermal variation, and characterizing this thermal variation is needed for assessing climate change impacts on headwater species accurately. Copyright © 2013 John Wiley & Sons, Ltd.

KEY WORDS: climate change; fish conservation; groundwater; Salmonidae; stream discharge; water temperature

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INTRODUCTION

Stream temperature exerts a predominant influence on distributions and abundance of fish. Climate change, with potentially strong but likely spatially variable effects on stream temperatures, is a major threat to population persistence of stream fishes (Ficke *et al*., 2007). Stream temperatures have already risen for the past few decades across the USA (Kaushal *et al*., 2010). The Northeastern USA has experienced an air temperature increase of 0.25 °C per decade since 1970 (Hayhoe *et al*., 2007), and climate models typically project a hotter summer with reduced streamflow over the coming decades (Hayhoe *et al*., 2007; Huntington *et al*., 2009). Such summer conditions would particularly impact coldwater species in small, headwater streams, but the extent of spatial variation in stream temperature resiliency has not been well characterized.

Stream temperatures have been estimated with an array of approaches. Physical models characterize heat energy exchange and transport within stream systems by accounting for interactions among various meteorological and hydraulic factors (including groundwater) (Sinokrot *et al*., 1995; Gu and Li, 2002; Gaffield *et al*., 2005). A simpler, yet successful, approach is to model stream and air temperature relationships based on the premise that stream–air heat exchange is the single most important mechanism regulating stream temperature (Mohseni *et al*., 1998; Caissie *et al*., 2001; Cooney *et al*., 2005; Morrill *et al*., 2005). The stream–air temperature relationship has been most typically characterized by a sigmoidal (S-shaped) curve, rather than a straight line, at hourly, daily and weekly time scales (Mohseni *et al*., 1998; Webb *et al*., 2003; Koch and Grünewald, 2010).

Earlier studies of climate change impacts on stream fish took advantage of the strong relationship between stream and air temperatures, by assuming that local streams in a region behave uniformly in response to increased regional

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air temperature (Meisner, 1990; Eaton and Scheller, 1996; Rahel *et al.*, 1996; Flebbe *et al.*, 2006; Rieman *et al.*, 2007; Williams *et al.*, 2009; Lyons *et al.*, 2010). They showed broad-scale patterns of potential habitat loss and fragmentation, in which stream fish populations were predicted to be increasingly relegated to cold or high-elevation basins. However, stream temperatures may vary longitudinally on the scale of kilometres or shorter because of geomorphologic and hydraulic factors, and tributary influences (Selker *et al.*, 2006). Broad-scale analysis based on regional air/stream temperature relationships would overlook localized stream segments that could act as remnant habitats and thermal refuges for stream fishes (Velasco-Cruz *et al.*, 2012).

Knowledge of fine-scale thermal heterogeneity is indeed paramount to effective conservation of brook trout *Salvelinus fontinalis*. Brook trout is native to eastern North America, and the species is widely recognized as an indicator of high-quality coldwater streams in its native range (Lyons *et al.*, 1996; Kanno *et al.*, 2010). Many populations of brook trout have been locally extirpated because of various types of anthropogenic activities (Hudy *et al.*, 2008). However, given suitable thermal regimes and under certain demographic conditions, brook trout populations can persist in short stream segments (<1 km) isolated by physical barriers such as waterfalls (Letcher *et al.*, 2007; Kanno *et al.*, 2011a). Therefore, understanding fine-scale heterogeneity of stream temperatures will help in identifying and prioritizing brook trout habitat and populations for conservation.

This study examined fine-scale stream temperature heterogeneity in two headwater brook trout stream networks (7.7 and 4.4 km) in Connecticut, USA. A combined total of 36 pairs of stream and air temperature loggers was deployed at approximately 300 m apart from each other. Data collection coincided with a hot and dry summer of 2010 (the second hottest summer on record in the region), a pattern that is predicted to increase by climate models for the study region (Hayhoe *et al.*, 2007; Huntington *et al.*, 2009). Paired stream–air temperature data, recorded hourly, were analysed using the nonlinear regression model of Mohseni *et al.* (1998).

METHODS

Study sites

The study was conducted in two headwater stream networks located in northwestern Connecticut, USA (Figure 1). The drainage area at the most downstream point was 14.56 km^2 in Jefferson Hill–Spruce Brook and 14.06 km^2 in Kent Falls

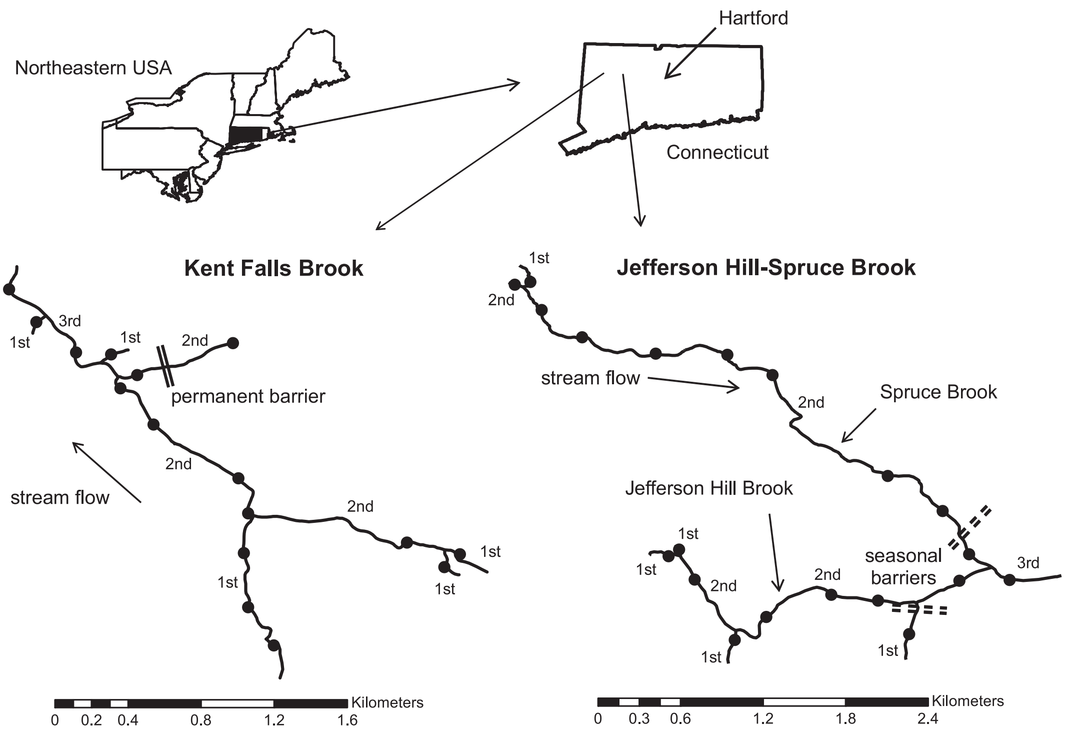

Figure 1. Locations of Jefferson Hill–Spruce Brook and Kent Falls Brook in the State of Connecticut, Northeastern USA. Circles indicate the locations of paired stream–air temperature loggers. Stream order (1:24,000 scale) is shown along stream flowlines (first, second and third order). Barriers refer to natural falls that impede upstream movement of brook trout (permanent > 5 m, and seasonal 1.5–2.5 m in height)

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Brook. The study networks were located on first- to third-order streams on the 1:24,000 scale (Figure 1). Both study streams contained self-reproducing brook trout populations. They represent brook trout habitat characteristics in the region; high-gradient, well-shaded headwater streams characterized by boulder, cobble, pebble and gravel substrate; mean stream wetted width was 4.3 m in Jefferson Hill–Spruce Brook and 4.8 m in Kent Falls Brook under summer base flow. Other common fish species observed were blacknose dace *Rhinichthys atratulus*, longnose dace *Rhinichthys cataractae* and white sucker *Catostomus commersoni* in Jefferson Hill–Spruce Brook, and blacknose dace and non-native brown trout *Salmo trutta* in Kent Falls Brook. Population ecology and genetics of brook trout had been studied extensively in the study sites (Kanno *et al*., 2011a, 2011b, 2012). Stream temperature modelling described here is part of the broader effort to understand mechanisms of persistence of small, headwater brook trout populations.

Temperature data collection

Pairs of temperature loggers were deployed to measure stream and air temperatures throughout the two study streams between 27 March and 21 October 2010. Previous studies of stream and air temperature modelling often used air temperature data recorded at the nearest weather stations (e.g. Mohseni *et al*., 1998; Caissie *et al*., 2001; Webb *et al*., 2003). In this study, air temperature data were also collected in the field to reflect local air temperature patterns experienced by streams more accurately. Stream and air temperatures were recorded hourly using HOBO temperature data loggers (±0.2 °C accuracy, Model U22-001, Onset Computer Inc., Bourne, MA, USA).

An attempt was made to place a pair of stream and air temperature loggers at the interval of approximately 300 m from each other, in order to assess fine-scale thermal heterogeneity within stream channel networks. Some stream temperature loggers were lost because of high streamflow and vandalism. Complete data (i.e. no missing values) were available for a total of 36 logger pairs for the data collection period: 20 pairs in Jefferson Hill–Spruce Brook (7.7 km of stream network length) and 16 pairs in Kent Falls Brook (4.4 km of stream network length) (Figure 1). Stream temperature loggers were deployed in deeper, slower-flowing sections where streamflow was well mixed. Air temperature loggers were deployed on tree branches or trunks at approximately 1.5-m high located 5–20 m from the stream section, in which their corresponding stream loggers were deployed. Each air temperature logger was covered in a PVC pipe to minimize the effect of direct solar radiation.

In addition to the paired stream–air temperature measurements taken in 2010, stream temperature (but not air temperature) was recorded at the identical stream sections between July 2008 and December 2009. The three summers covered during this period were distinguishable from each other on the basis of air temperature and precipitation patterns. Weather data in the city of Hartford, located in mid-central Connecticut (Figure 1), illustrate summer characteristics experienced across the state (Table 1). The mean air temperature for July (24.2 °C) and August (21.1 °C) of 2008 approximated historical mean values ($\pm < 1\,^\circ$C), and precipitation during these months was higher than an average year. In 2009, the July mean air temperature (21.8 °C) was 1.5 °C cooler than the average, but the August mean air temperature was 2 °C higher than the average. Plus precipitation in July 2009 (245.33 mm) nearly tripled the monthly mean. Notably, summer of 2010 was the hottest and driest during these three summers; in fact, it was the second hottest summer in the study region to date. The climate pattern of summer 2010 is predicted to increase for the study region under climate change scenarios (Hayhoe *et al*., 2007; Huntington *et al*., 2009).

Statistical analysis

Hourly stream–air temperature data were analysed using the nonlinear regression method of Mohseni *et al*. (1998). The method fits a sigmoidal (S-shaped) curve between stream and air temperatures on the basis of known physical properties of stream temperature. That is, the vapour pressure deficit above a water surface increases drastically, causing strong evaporative cooling at elevated air temperatures,

Table I. Weather characteristics (mean air temperature, mean daily maximum air temperature and total precipitation) for July and August of 2008–2010 in Hartford (Hartford-Brainard Airport), located in middle central Connecticut (data available at http://www.tutiempo.net/en/)

	2008		2009		2010		Long-term average	
	July	Aug	July	Aug	July	Aug	July	Aug
Mean temp. (°C)	24.2	21.1	21.8	23.7	25.9	23.7	23.3	21.7
Mean daily max. (°C)	29.5	26.9	27.2	28.8	31.5	29.3	28.9	27.2
Precipitation (mm)	160.24	157.98	245.33	99.57	45.47	66.29	91.44	86.36
Temperature data	Stream only		Stream only		Stream–air pair			

whereas stream temperatures typically reach 0 °C as an asymptote at low air temperatures (Mohseni and Stefan, 1999). The nonlinear regression is expressed as

$$T_s = \mu + \frac{\alpha - \mu}{1 + e^{\gamma(\beta - T_\alpha)}} \tag{1}$$

where T_s represents stream temperature and T_α represents air temperature. There are four parameters to be estimated: μ is the minimum stream temperature; α is the maximum stream temperature; γ is the function of the steepest slope (inflection point); and β is the air temperature at the inflection point (Mohseni *et al.*, 1998). The estimated parameters of this model can thus be physically interpretable. However, it should be kept in mind that the study period was between March and October 2010, and the coldest months were missing from our data set. Therefore, parameter estimates are not comparable with those studies based on year-round stream temperature data sets (e.g. Mohseni *et al.*, 1998; Morrill *et al.*, 2005), and they will not be reported here.

The nonlinear regression was fit for each pair of loggers and each hour of the day, resulting in a total of 864 unique regressions (i.e. 36 loggers × 24 h). This approach was taken to assess spatial and diurnal thermal patterns. Models were fit using JAGS (Plummer, 2011) called from R (R Development Core Team, 2011) with the rjags package. The simplest application of this nonlinear regression method was to compare time-series stream and air temperature data during the study period (March to October 2010). In addition, this study assessed a potential improvement in model fit by accounting for time lag and seasonal effects (i.e. hysteresis). Specifically, the regression method was applied using different time lag intervals (0, 1, 2, 3 and 4 h), in which stream temperatures were regressed against air temperature measurements taken 0–4 h earlier. Hysteresis was considered by using all data available during the study period (March to October) versus records up to July. Stream temperature may respond to air temperature differently during the warming season (up to summer) and the cooling season (after summer) (Mohseni *et al.*, 1998). The unique combination of five time lag intervals and two data periods resulted in 10 different data sets, for each of which 864 nonlinear regression models were constructed. In order to compare model fit among the 10 data sets, the Nash–Sutcliffe coefficient (NSC) (Mohseni *et al.*, 1998) was calculated for each nonlinear regression model as

$$NSC = 1 - \frac{\sum_{i=1}^{n}\left(T_{\mathrm{sim},i} - T_{\mathrm{obs},i}\right)^2}{\sum_{i=1}^{n}\left(T_{\mathrm{obs,mean}} - T_{\mathrm{obs},i}\right)^2} \tag{2}$$

where T_{sim} is simulated (estimated) stream temperature value, T_{obs} is observed stream temperature values and $T_{\mathrm{obs,mean}}$ represents mean observed stream temperature for the logger. *NSC* has a maximum score of 1 (perfect model fit) and no minimum; *NSC* values > 0 are considered satisfactory (Morrill *et al.*, 2005). Ten data sets were compared on the basis of the mean *NSC* value across 864 nonlinear regression models, and

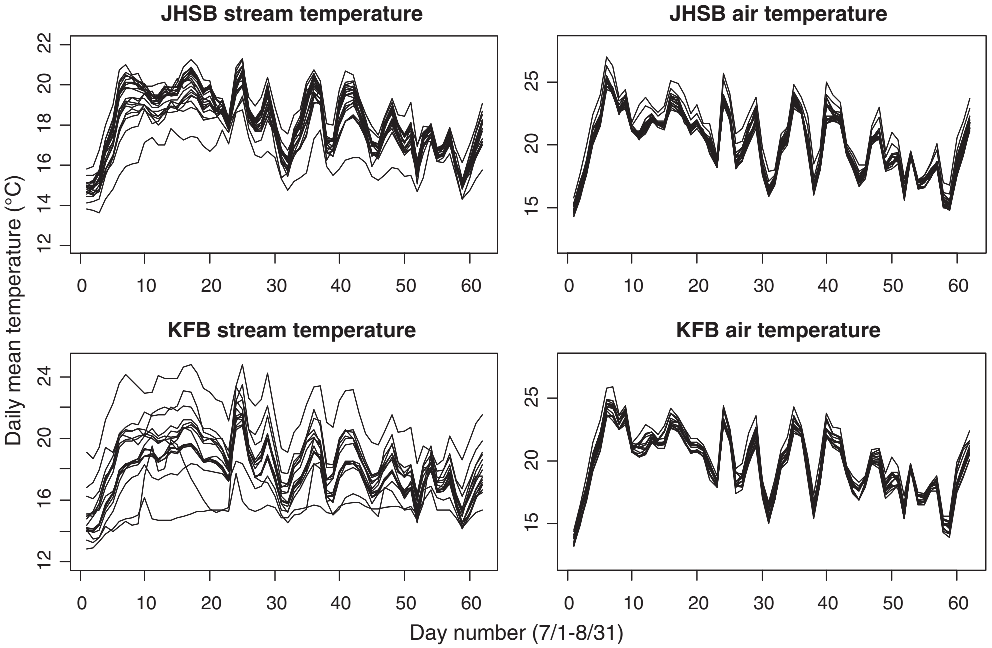

Figure 2. July–August daily mean stream and air temperature of 20 loggers in Jefferson Hill–Spruce Brook (JHSB) and 16 loggers in Kent Falls Brook (KFB). Each line represents a temperature logger

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Table II. July–August mean stream temperature (°C) between 2008 and 2010

	July			August		
	2008[a]	2009	2010	2008	2009	2010
Jefferson Hill–Spruce Brook						
Mean	18.6	16.1	18.4	16.5	17.5	17.4
Range	17.7–19.3	15.5–16.7	16.5–19.5	16.0–17.2	16.6–18.1	15.8–18.4
Kent Falls Brook						
Mean	19.0	17.4	18.6	16.8	18.7	17.5
Range	16.5–22.9	14.8–20.3	15.0–22.7	15.3–20.2	16.3–21.7	15.4–20.6

Values indicate the mean and range across 20 loggers in Jefferson Hill–Spruce Brook and 16 loggers in Kent Falls Brook.

[a] In 2008, stream temperature data were available on and after 15–16 July in Jefferson Hill–Spruce Brook and 14 July in Kent Falls Brook.

the data set with the highest mean *NSC* value was chosen as the best fitting set.

RESULTS

Descriptive statistics

Stream temperatures increased from March to July before decreasing towards October. The mean value of 2010 July mean temperature across 20 loggers was 18.4 °C in Jefferson Hill–Spruce Brook and 18.6 °C in Kent Falls Brook (16 loggers). Spatial thermal variability among loggers was larger during warmer months relative to cooler months. For example, the range of July mean temperature was 3 °C (16.5–19.5 °C) among 20 loggers in Jefferson Hill–Spruce Brook, whereas the range of April mean temperature was 1.3 °C (8.6–9.9 °C). The range of July mean temperature was more widespread among 16 loggers in Kent Falls Brook (15.0–22.7 °C) because of the presence of both cold and warm tributaries (see succeeding text). In contrast to the spatially variable stream temperature, summer air temperature was nearly identical among loggers in both streams (Figure 2).

Stream temperature in 2010 July–August was comparable with those of the previous 2 years (Table 2), although this was the hottest and driest summer of the three. In both study streams, the mean of July temperature across loggers was highest in 2008, and the mean of August temperature across loggers was highest in 2009 (Table 2). In fact, some tributaries maintained cooler stream temperature in 2010 July–August than 2008 or 2009. For example, July–August stream temperature in a Jefferson Hill tributary was 16.5 °C in 2008, 16.2 °C in 2009 and 16.1 °C in 2010. A tributary in Kent Falls Brook similarly had the lowest July–August temperature in 2010 (15.2 °C), compared with 2008 (15.7 °C) and 2009 (15.5 °C).

During summer of 2010, fine-scale thermal variability was primarily found between tributary sites and between tributary and mainstem sites in Kent Falls Brook (Figure 3). Three

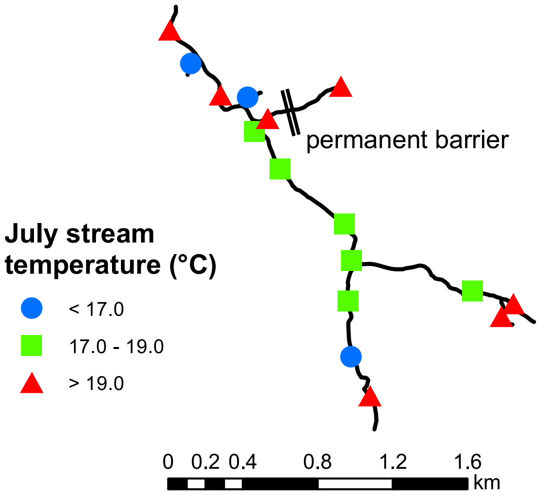

Figure 3. Spatial heterogeneity in July mean stream temperature within Kent Falls Brook in 2010. This figure is available in colour online at wileyonlinelibrary.com/journal/rra

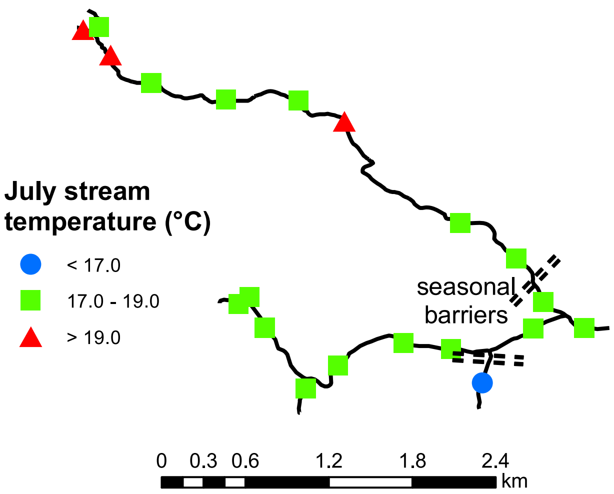

Figure 4. Spatial heterogeneity in July mean stream temperature within Jefferson Hill–Spruce Brook in 2010. This figure is available in colour online at wileyonlinelibrary.com/journal/rra

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Table III. *NSC* values of the nonlinear regression model applied to 10 data sets with unique combinations of time lag and seasonal effect (i.e. hysteresis)

Data sets	Mean *NSC* value
0-h lag, all data	0.791
1-h lag, all data	0.805
2-h lag, all data	0.815
3-h lag, all data	0.819
4-h lag, all data	0.819
0-h lag, data up to 31 July	0.823
1-h lag, data up to 31 July	0.836
2-h lag, data up to 31 July	0.845
3-h lag, data up to 31 July	0.849
4-h lag, data up to 31 July	0.847

Values represent the mean across 864 regressions (i.e. 36 loggers × 24 h). NSC, Nash–Sutcliffe coefficient.

loggers recorded July mean stream temperature < 17 °C in Kent Falls Brook and the coldest logger recorded 15.0 °C. Kent Falls Brook also included warm tributaries (July mean stream temperature > 19 °C). Jefferson Hill–Spruce Brook was more thermally homogeneous (Figure 4). Still, one semi-isolated tributary (above a seasonal barrier) maintained a cooler July mean stream temperature (16.5 °C) relative to other loggers in this network (Figure 4).

Nonlinear regression analysis

Time lag and seasonal effect (hysteresis) were found important in the analysis of 2010 paired stream–air temperature data. On the basis of the mean *NSC* value across 864 logger × hour combinations, the nonlinear regression method had the best fit when it was applied to data up to July, with a 3-h time lag (Table 3). Analyses based on data up to July had higher mean *NSC* values than those based on all available data (March–October), indicating that stream–air temperature relationships differed before and after summer. Among analyses based on March to July data, increasing time lag from 0 to 3 h improved model fit slightly (Table 3). The mean *NSC* value of the best fitting model was high (0.849), indicating that the sigmoidal shape was appropriate for the stream–air temperature data of this study. The following results are based on the best model (i.e. 3-h time lag and based on March–July records).

Stream–air temperature relationships varied spatially and diurnally (Figure 5). Stream temperature typically peaked in the afternoon to the evening; these hours were when spatial thermal variability was largest. For example, predicted stream temperatures differed by >10 °C at 16 and 20 o'clock when air temperature was >30 °C (Figure 5). A large temperature variation was observed between a cold tributary and a warm tributary in Kent Falls Brook. The

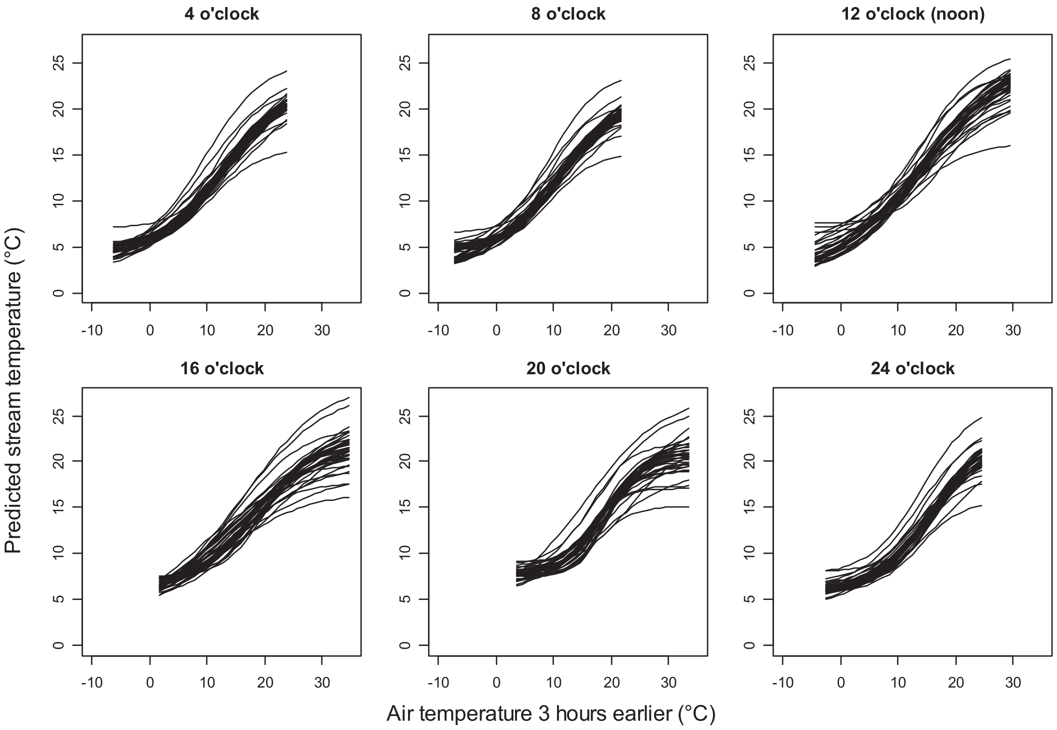

Figure 5. Stream–air temperature relationship predicted by the nonlinear regression method at selected hours. All 36 loggers are shown in each panel. The *x*-axis range represents minimum and maximum air temperature values recorded at that hour

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maximum stream temperature difference recorded between these tributaries was 11.46 °C at 20 o'clock on 26 May 2010.

There were roughly three groups of stream reaches that were distinguishable on the basis of temperature data: mainstem, cold tributaries and warm tributaries. Stream–air temperature patterns were visually similar among mainstem loggers. Stream–air relationships at an example mainstem logger in Jefferson Hill Brook showed that stream temperature increased rather linearly with air temperature, except at warm hours of the day when the sigmoidal pattern became evident (Figure 6). In cold tributaries, the sigmodal pattern was more noticeable, and stream temperature appeared to reach an asymptote at warm hours in a tributary in Kent Falls Brook (Figure 7). In warm tributaries, stream–air temperature relationships were rather linear even at 16 and 20 o'clock (Figure 8). In all three groups, stream–air temperature data points were more variable at warmer times (16 and 20 o'clock) of the day (Figures 6–8). This common pattern was represented by lower mean *NSC* values across loggers in the afternoon and evening, relative to other times of the day (Table 4).

DISCUSSION

The detailed monitoring of stream temperature in headwater brook trout stream networks provided new perspectives on the fine-scale spatial thermal heterogeneity and potential impact of climate change on coldwater resources. Regional-scale studies of climate change impact on stream fish distributions have provided useful initial insights on the potential degree of habitat loss and fragmentation (Meisner, 1990; Eaton and Scheller, 1996; Rahel *et al*., 1996; Flebbe *et al*., 2006; Rieman *et al*., 2007; Williams *et al*., 2009; Lyons *et al*., 2010). These studies typically assumed that local streams in a region would experience identical rates of stream temperature increase. However, our study showed that thermal heterogeneity existed within local stream networks, and resiliency of stream temperature under climate change might differ at the local scale. As a result, climate change impacts on stream fish distributions might have been over-predicted in previous studies. Velasco-Cruz *et al*. (2012) also reported spatial variability in stream–air temperature relationships among brook trout streams in Virginia, USA.

Groundwater appears to play a pivotal role in creating fine-scale thermal heterogeneity within study watersheds. The importance of groundwater in mediating stream temperature can also be inferred from the 3-year stream temperature data (2008–2010). For example, the mean air temperature of August was identical (23.7 °C: Table 1) between 2009 and 2010 (but mean daily maximum air temperature was higher in 2010), but August 2009 had more precipitation than

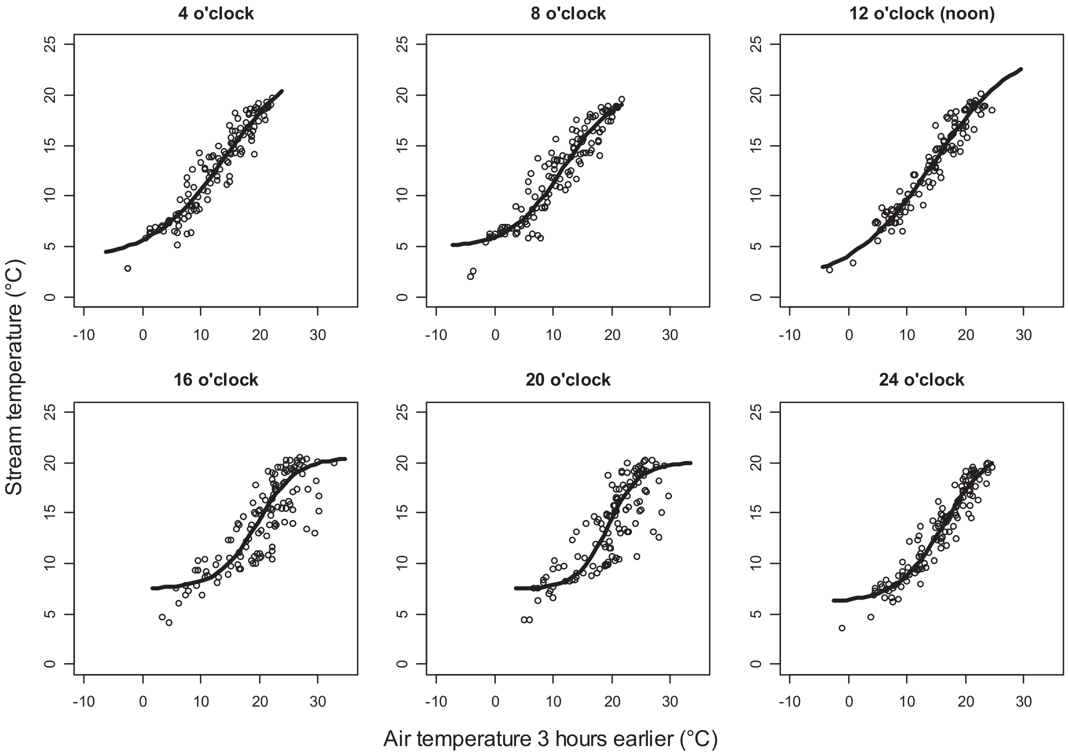

Figure 6. Stream–air temperature relationship at selected hours at an example mainstem logger in Jefferson Hill Brook. The nonlinear regression line is based on the 3-h lag model using data up to July

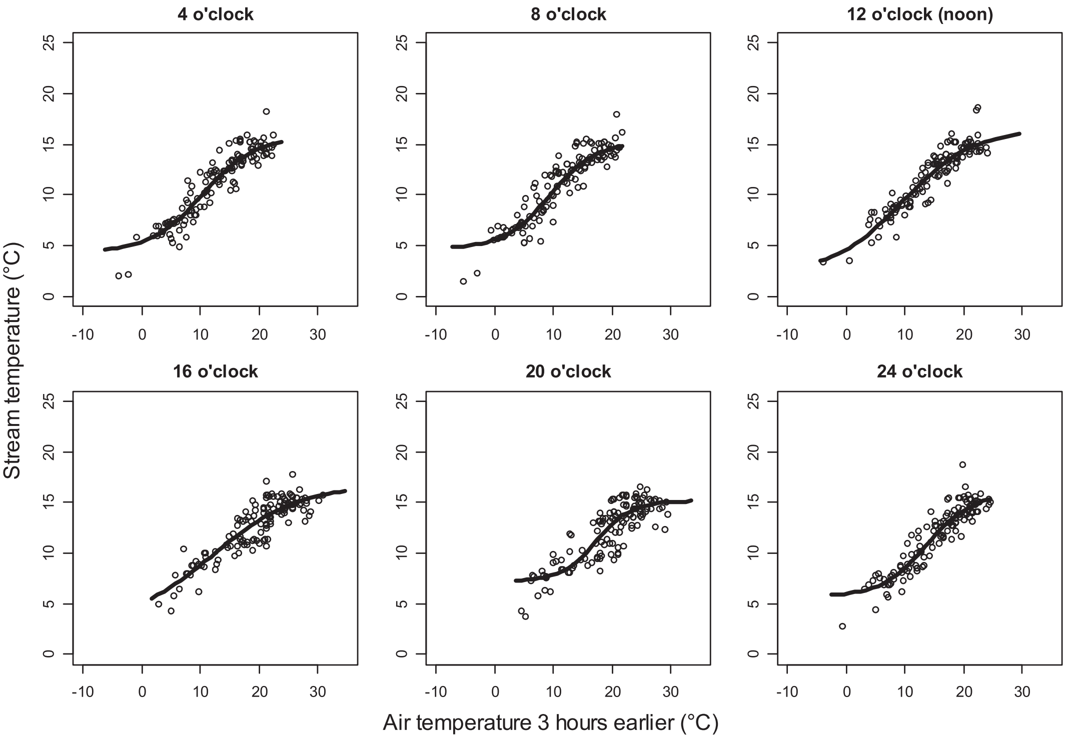

Figure 7. Stream–air temperature relationship at selected hours at an example cold tributary logger in Kent Falls Brook. The nonlinear regression line is based on the 3-h lag model using data up to July

August 2010. Yet in Kent Falls Brook, August mean stream temperature was noticeably cooler in 2010 (mean 17.5 °C) than in 2009 (18.7 °C) (Table 2). Similarly, July stream temperature in both study sites was nearly identical between 2008 and 2010 (Table 2) although July 2010 was hotter and drier than July 2008 (Table 1). These observations suggest that summer stream temperature dominated by groundwater during base-flow conditions may remain cooler, relative to hot summers with more precipitation in which surface water accounts for a higher portion of streamflow. This is an interesting mechanism that has been reported particularly in small headwater streams (Gaffield *et al.*, 2005; Kelleher *et al.*, 2012), whereas negative correlation between stream temperature and flow volume has been documented in larger streams and rivers (Webb *et al.*, 2003; van Vliet *et al.*, 2011). Chu *et al.* (2009) similarly found that groundwater contributed to lower stream temperatures despite an increase in air temperatures in Ontario streams.

A hotter and drier summer is predicted over the coming decades in the Northeastern USA (Hayhoe *et al.*, 2007; Huntington *et al.*, 2009), but its impact on stream temperature and thermal habitat is likely to vary spatially (Chu *et al.*, 2008). Groundwater temperatures approximate mean annual air temperatures (Power *et al.*, 1999), and this is why a 1 °C increase in air temperature was translated into a stream temperature increase of 1 °C in many studies (Meisner, 1990; Rahel *et al.*, 1996; Flebbe *et al.*, 2006; Rieman *et al.*, 2007; Williams *et al.*, 2009). However, the magnitude and speed of groundwater temperature change depends upon volume (Gunawardhana *et al.*, 2011; Neukum and Azzam, 2012) and depth (Taylor and Stefan, 2009; Deitchman and Loheide, 2012; Gunawardhana and Kazama, 2012) of groundwater at the local scale. Importantly, spatial variability in resiliency of groundwater temperature in response to air temperature is the critical missing piece to assess climate change impacts on headwater stream fish accurately.

Several tributaries maintained thermally suitable habitat for brook trout in this study. These tributaries had July mean stream temperature <17 °C, and their current summer stream temperature is a few degrees below a thermally stressful temperature for brook trout. Hartman and Cox (2008) showed that metabolic rates increased with water temperature up to 20 °C before declining precipitously at a higher temperature. Velasco-Cruz *et al.* (2012) considered 21 °C as thermally stressful for brook trout in assessing vulnerability of Virginia streams to climate change. If these tributaries indeed remain thermally resilient and suitable under climate change, such short stream sections would play an important role in brook trout conservation. Our previous work documented that brook trout populations can persist in short, isolated stream sections (<1 km: Letcher *et al.*, 2007; Kanno *et al.*, 2011a). For example, the July mean stream

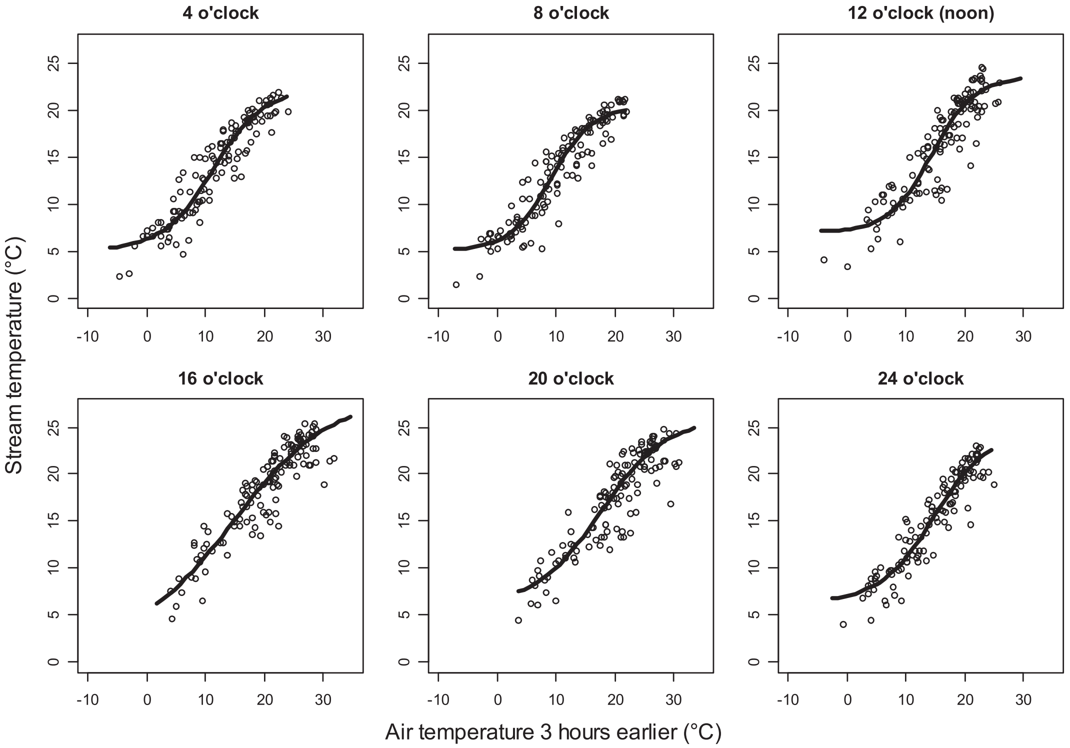

Figure 8. Stream–air temperature relationship at selected hours at an example warm tributary logger in Kent Falls Brook. The nonlinear regression line is based on the 3-h lag model using data up to July

temperature of a semi-isolated tributary in Jefferson Hill Brook was 16.5 °C. The population in this first-order tributary is nearly completely isolated because of natural falls (‘seasonal barrier’ on Figure 4), and brook trout movement is unidirectional from the tributary to the mainstem (Kanno *et al.*, 2011a). This tributary population does not rely upon immigration to persist. Thus, the population is likely to remain viable as long as its habitat characteristics, including stream temperature, remain suitable even though brook trout abundance may decline immediately downstream in the mainstem.

Table IV. Mean *NSC* value across 36 loggers at even hours

Time of the day (o’clock)	Mean *NSC* value
2	0.902
4	0.903
6	0.907
8	0.896
10	0.892
12	0.901
14	0.786
16	0.770
18	0.730
20	0.740
22	0.847
24	0.905

NSC, Nash–Sutcliffe coefficient.

Our approach using deployment of paired loggers is conceptually simple and logistically feasible for management agencies, and yet it provides sufficiently useful information for understanding spatial and diurnal heterogeneity in stream temperature patterns. In retrospect, one air temperature logger in each of the two stream networks would have sufficed because there was little variability in air temperature among loggers within each network. Future efforts to replicate our study design would not require multiple air temperature loggers in a small watershed such as ours. Deployment of stream temperature loggers is not as straightforward. Spatial variability in stream temperature was primarily observed between stream segments, and stream temperature typically varied less within a stream segment (i.e. from confluence to confluence). Thus, one stream temperature logger per segment could be sufficient to understand fine-scale stream temperature heterogeneity in many instances, although it might not work well when stream temperature varies within a stream segment because of, for example, localized groundwater seeps (Selker *et al.*, 2006).

Given its declining population trend (Hudy *et al.*, 2008) and high recreational value, conservation effort of brook trout remains important in its native range. Because brook

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trout is an indicator of high-quality coldwater streams (Lyons *et al*., 1996; Kanno *et al*., 2010), protecting brook trout thermal habitats would also benefit the associated coldwater biotic community. This study showed that one potential focus area in conservation efforts may be to identify and protect existing streams whose stream temperatures are less sensitive to air temperature increase; thus, these streams are likely to provide the best habitat characteristics for brook trout under climate change. This exercise should ideally be conducted at the regional scale; regional stream temperature data sets are rare presently. Temporal coverage is similarly limited for stream temperature data; there exists no temperature gages at the national scale in USA, such as the streamflow gages operated by the US Geological Survey. Understanding spatial and temporal patterns of stream temperature is paramount to the conservation and management of aquatic resources in the coming decades, and further research is warranted in this important topic.

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